Department of Energy Office of Energy Efficiency and Renewable Energy

High Efficiency, Low Emissions, Solid Oxide Fuel Cell Systems for Multiple Applications

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Abstract

Technology Management Inc. (TMI), teamed with the Ohio Office of Energy Efficiency and Renewable Energy, has engineered, constructed, and demonstrated a stationary, low power, multi-module solid oxide fuel cell (SOFC) prototype system operating on propane and natural gas. Under Phase I, TMI successfully operated two systems in parallel, in conjunction with a single DC-AC inverter and battery bus, and produced net AC electricity. Phase II testing expanded to include alternative and renewable fuels typically available in rural regions of Ohio. The commercial system is expected to have ultra-low pollution, high efficiency, and low noise.

The TMI SOFC uses a solid ceramic electrolyte operating at high temperature (800-1000 °C) which electrochemically converts gaseous fuels (hydrogen or mixed gases) and oxygen into electricity. The TMI system design oxidizes fuel primarily via electrochemical reactions and uses no burners (which pollute and consume fuel) -- resulting in extremely clean exhaust. The use of proprietary sulfur tolerant materials developed by TMI allows system operation without additional fuel pre-processing or sulfur removal. Further, the combination of high operating temperatures and solid state operation increases the potential for higher reliability and efficiencies compared to other types of fuel cells.

Applications for the TMI SOFC system cover a wide range of transportation, building, industrial, and military market sectors. A generic technology, fuel cells have the potential to be embodied into multiple products specific to Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) program areas including: Fuel Cells and Microturbines, School Buildings, Transportation, and Bioenergy. This program focused on low power stationary applications using a multi-module system operating on a range of common fuels.

By producing clean electricity more efficiently (thus using less fuel), fuel cells have the triple effect of cleaning up the environment, reducing the amount of fuel consumed and, for energy intensive manufacturers, boosting their profits (by reducing energy expenses). Compared to conventional power generation technologies such as internal combustion engines, gas turbines, and coal plants, fuel cells are extremely clean and more efficient, particularly at smaller scales.

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Executive Summary

Project Background

Technology Management Inc. (TMI) teamed with the Ohio State Office of Energy Efficiency and Renewable Energy to engineer, construct, and test a stationary, low power, multi-module solid oxide fuel cell (SOFC) prototype system operating on propane and natural gas. Multiple objectives were served in sequence by each phase of this project.

- *Phase I focused on configuring the system to operate on multiple, low power modules, with each module operating on natural gas or propane.* Since each module is a free-standing system, this configuration shows how redundancy is an inherent feature of the multi-module design and the potential for increasing overall systems reliability. Reliability is critical to establish end user confidence in and demand for fuel cell systems, especially as an alternative to grid service. Other goals of this research were
 - to generate technical and operating information describing multi-module systems operation on common fuels.
 - engineering a power storage and power conditioning subsystem control suitable for multi-module systems.
- Phase II focused on demonstrating fuel compatibility with kerosene and biofuels, both considered alternative and/or renewable fuels. Kerosene contains sulfur, which is a known poison to almost every known fuel cell system, except the TMI SOFC system.

By producing clean electricity more efficiently (thus using less fuel), fuel cells have the triple effect of cleaning up the environment, reducing the amount of fuel consumed and, for energy intensive manufacturers, boosting their profits (by reducing energy expenses). Compared to conventional power generation technologies such as internal combustion engines, gas turbines, and coal plants, fuel cells are extremely clean and more efficient, particularly at smaller scales.

The TMI system design oxidizes fuel primarily via electrochemical reactions and uses no burners (which pollute and consume fuel) -- resulting in an extremely clean exhaust. ^[1]

Commercialization

To position its system toward niche market and applications, TMI has engineered product features which differentiate the TMI system from all other fuel cell systems. These features include:

- **Multiple Fuel Compatibility:** The system has been tested on multiple common available fuels, including those containing sulfur, a known poison to most fuel cell systems.
- **Compactness:** Systems have been packaged to meet the size and weight limitations required for overnight delivery by common carriers (e.g., Fedex, UPS).
- **Low power:** Systems scaled down to as low as 300 watts operating on common available fuels have been demonstrated (allowing multi-module configurations as low as 1 kW).
- **Multi-module Design:** The system is designed for multiple module operation and the inherent benefits of redundancy for higher reliability, backup, and ease of service.

¹ Total organics, particulates, and CO are expected to be essentially zero. Levels of NO_x are expected to be less than 1 ppm. Emissions of CO₂ and SO₂ will be lower than for engine-based systems due to the higher fuel efficiency of fuel cell systems.

The features described above, taken collectively, position the TMI system for niche applications in the 1 to 20 kW range, where high reliability, compactness and cost effectiveness, over other power generation modalities, will be advantageous in market entry niches. No other known systems have this combination of features. To achieve higher overall power levels with increased reliability, TMI connects in parallel completely independent system modules. At production levels forecast for 2010, manufacturing costs are forecast below \$500 per kW. ^[2]

Technical Approach

The primary objective of this program was to design, build and demonstrate a multi-module prototype SOFC subsystem (with primary power conditioning and energy storage capability). The system would have the potential to operate on multiple fuels, including conventional (Phase I - natural gas and propane; Phase II - kerosene) and renewable fuels (biogas in Phase II).

A key element of the TMI strategy to achieve a robust range fuel compatibility, including some which contain sulfur, ^[3] is the use of the TMI sulfur-tolerant 500-Watt portable power generation system as a building block for larger power configurations. Integrated with storage batteries to handle surge and power peak requirements, this allows the system to produce sufficient power for base loads as well as load following.

Conclusions

Over the course of this two-year program, TMI designed and built three kilowatt-class stand-alone systems. Approximately twenty 300W class tests were conducted with an accumulated 15,000 hours of test time. Over 90% of the test runs were on hydrocarbon fuels. The system studies demonstrated the feasibility of operating multiple TMI SOFC systems on multiple fuels and showed that even at relatively low power (<300W), net efficiencies near 25% DC LHV on natural gas fuel can be achieved using standard balance of plant components. Several special conditions were examined. These included 1) on-the-fly switching between different hydrocarbon fuels (with no break in output power) and 2) stand-alone mobile operation on bottled propane.

The study also produced insights on the use (and limitations) of standard, off-the-shelf components. The findings indicated a need for specialized subsystems which are optimized for fuel cell operation. Additional study is required to further characterize the operating parameters of the systems, particularly when multiple systems are run in parallel.

² Estimates were calculated internally at Technology Management Inc.

³ Sulfur is known to poison most fuel cells at very low concentrations. From J.H. Hirschenhofer, D.B. Stauffer, R.R. Engleman, and M.G. Klett "Fuel Cell Handbook, Fourth Edition", November 1998 written under contract #DE-AC21-94MC31166 of the DOE Department of Fossil Energy.

Experimental

Background

Technology Management Inc. (TMI) teamed with the Ohio State Office of Energy Efficiency and Renewable Energy to engineer, construct, and test a stationary, low power, multi-module solid oxide fuel cell (SOFC) prototype system operating on propane and natural gas. Phase II expanded testing to include other alternative and renewable fuels available in rural regions of Ohio. Of particular interest were fuels that might contain considerably higher levels of sulfur such as kerosene and agricultural fuels including ethanol and biodiesel. The test unit contained two (2) modules (each "module" is a complete independent system) having an advanced systems configuration which provided backup and improved reliability. The eventual commercial low power system is expected to be scalable by adding more modules to provide higher levels of power output. The commercial system is also expected to have ultra-low-pollution, high efficiency, and low noise.

Objectives

Different objectives were served in each phase. *Phase I focused on the system integration of multiple, low power modules operating on natural gas and propane.* The multi-module configuration also demonstrates systems reliability, critical to create end-user confidence in and demand for fuel cell systems, especially as an alternative to grid service. Since TMI has successfully demonstrated *single* systems operating in the laboratory, a goal was to generate operating data describing multi-module systems operation on common fuels. Other key subtasks in Phase I included engineering a power storage and power conditioning subsystem control suitable for multi-module systems. *Phase II focused on system performance operating on kerosene and biofuels*, considered an alternative and/or renewable fuels. A second aspect of the fuel selection was because of the higher sulfur levels of kerosene and certain agricultural fuels such as ethanol and biodiesel. Sulfur, is a known poison to almost every known fuel cell system, except the TMI SOFC system.

Commercialization

To position its system toward niche market and applications, TMI has engineered product features which differentiate the TMI system from all other fuel cell systems. These features include:

- Multiple Fuel Compatibility: The system has been tested on multiple common available fuels, including those containing sulfur, a known poison to most fuel cell systems.
- Compactness: Systems have been packaged to meet the size and weight limitations required for overnight delivery by common carriers (e.g., Fedex, UPS).
- Low power: Systems scaled down to as low as 300 watts operating on common available fuels have been demonstrated (allowing multi-module configurations as low as 1 kW).
- Multi-module Design: The system is designed for multiple module operation and the inherent benefits of redundancy for higher reliability, backup, and ease of serviceability.

The features described above, taken collectively, position the TMI system for niche applications in the 1 to 20 kW range, where high reliability, compactness and cost effectiveness, over other power generation modalities, will be advantageous in market entry niches. No other known systems have this combination of features. To achieve higher overall power levels with

increased reliability, the TMI system completely independent system modules in parallel. At production levels forecast for 2010, manufacturing costs are forecast below \$500 per kW.^[4]

Fuel Compatibility

The ability to use a wide variety of common fuels directly, particularly fuels containing sulfur contaminants, is a unique competitive advantage for entering niche markets. In comparison, other fuel cell systems handle sulfur by requiring specialty fuel preprocessing or adding fuel processing hardware which removes sulfur. Sulfur tolerance results achieved and reported by TMI for cells, stacks, and catalysts have shown excellent stability at levels up to 300 ppm H₂S at 950°C.^[5] Under the referenced DARPA program, TMI was one of the first fuel cell system developers to demonstrate a complete SOFC system operating *without sulfur-removal or fuel pretreatment*.^[6]

The primary goal of TMI's program was to design, build, and test a 1 kW prototype system operating on a variety of fuels with commercial objectives leading to implementation of a highly reliable, multi-fuel SOFC with multiple energy efficient applications. Potential niche markets for small multi-fuel systems are numerous and are discussed in more detail later. These include 1. End use applications where the cost of utility grid access is prohibitive (i.e., remote locations, industrial), 2. Markets where the available or preferred fuel for fuel cells contains sulfur (i.e., military, airports, rural, water treatment plant gases, village scale micro-grids, international), and 3. Markets where self-maintenance and reliability is not satisfactory i.e., high-density urban installations.

Systems Development Approach

The TMI team has specialized capability and experience in every major component area and was uniquely qualified to pursue these objectives for the Department of Energy Office of Energy Efficiency and Renewable Energy. Senior members of the team worked together for many years on similar projects. Previously, under funding from DARPA/ARO, TMI developed and demonstrated a fuel cell stack and fuel reformer "hot subassembly" that was mechanically and thermally integrated and could accommodate a wide range of potential fuel products including sulfur. Using this hot subassembly as a platform, TMI successfully engineered, constructed and operated a complete system that showed the feasibility of a small, compact, person-portable, power generation system operating directly on JP-8 (military kerosene). Throughout all its work, TMI applies product manufacturing cost, commercial viability and technology leverage metrics, even when selecting alternative technical approaches to problem solving.

TMI SOFC Technology

The TMI solid oxide fuel cell (SOFC) uses a solid ceramic electrolyte operating at high temperature (800-1000°C) to electrochemically convert gaseous fuels (hydrogen or mixed gases) and oxygen into electricity. Further, the combination of high operating temperatures and solid state operation increases the potential of the TMI SOFC to be very reliable, compact, and noiseless. The cell geometry is a simple, flat, featureless (two-inch diameter) disk and has the potential of very low unit cost of manufacture. Multiple cells are "stacked" to provide larger

4 Estimates were calculated internally at Technology Management Inc.

5 "TMI 500 Watt Sulfur Tolerant Solid Oxide Fuel Cell (SOFC) Battery Charger Operating Directly on Military Logistics Fuel", Dr. Robert Ruhl, 38th Power Sources Conference, Cherry Hill, NJ, June 8th-11th, 1998

6 Part of testing performed under DARPA/ARO Contract Number DAAD19-99C-0035.

amounts of power and integrated with a fuel reformer into a "hot assembly" which has been operated in the laboratory on a variety of common fuels such as natural gas, biogas, liquid biodiesel, and military logistic fuels (JP-8 jet fuel).

Figure 1 shows an expanded schematic to illustrate the TMI SOFC single cell with conventional SOFC materials. Each cell is made up of four layers: (1) a porous cermet anode that provides both fuel gas distribution and electrical continuity; (2) a pre-sintered, non-porous, yttria-stabilized zirconia (YSZ) electrolyte for selective ion conduction; (3) a porous ceramic cathode (LSM) that provides air distribution and electrical continuity; and (4) a high-temperature metallic alloy separator for bipolar electrical conduction from cell to cell.

Fuel and oxidant, are supplied through holes in the center of the cell and co-flow radially outward through the porous electrode pathways. Internal manifolding minimizes the seal perimeter area between the fuel and oxidant ports and eliminates the need for exhaust manifolds at the circumference of the cells. At the circumference, the remaining fuel and excess oxidant mix and react to virtually complete fuel oxidation before exiting as exhaust. The cell, at approximately two inches in diameter, is full commercial scale.

The TMI design has several advantages. The simple radial design utilizes an unconstrained perimeter that minimizes thermal expansion matching required by many other SOFC designs and allows for the incorporation of new or improved materials not feasible in cofired designs. The very simple, radial planar, non-featured cell components provide manufacturing flexibility by allowing the use of commercially available, high volume automated manufacturing technologies. The ability to produce the TMI SOFC at low unit cost is critical to achieving success in civilian commercial markets.

Another major demonstrated advantage of the TMI SOFC design is its ability to use a wide variety of fuels, particularly those containing sulfur contaminants, such as biogas, odorized

natural gas and military logistic fuels. Results have been presented that clearly demonstrate excellent stability when cells are switched from humidified hydrogen fuel to a 300 ppm H₂S spiked composition at 950°C.^[7] Under sponsorship by DARPA (Defense Advanced Research Agency), TMI operated a complete sulfur-tolerant system (with an integrated reformer and stack) demonstrating operation of a total SOFC system operating without sulfur-removal or fuel pretreatment.^[8]

Sulfur tolerance affords many advantages. These include system simplicity and fuel flexibility, which directly relate to system size, weight, and cost. A comparison between the TMI SOFC system strategy and a typical PEM (Proton Exchange Membrane Fuel Cell) is given in Figure 2.

System Design

System engineering calculations included both overall and detailed material and energy balances for the integrated system and for representative operating conditions. Using these balances and simulations of the fuel cell stacks and fuel processors, expected compositions of gas streams and key efficiency parameters (electrochemical conversion efficiency and electrochemical fuel utilization) were determined. The fuel cell stack simulations utilized a two-dimensional finite-difference electrochemical model, with variable fuel gas and oxidizer gas compositions, variable

7 "TMI 500 Watt Sulfur Tolerant Solid Oxide Fuel Cell (SOFC) Battery Charger Operating Directly on Military Logistics Fuel", Dr. Robert Ruhl, 38th Power Sources Conference, Cherry Hill, NJ, June 8th-11th, 1998

8 Part of development work sponsored by DARPA/ARO Contract Number DAAH04-94-C-0015, "500 Watt portable SOFC power generation system," and DARPA/ARO Contract Number DAAD19-99-C-0035, "Development of TMI logistic fuel solid oxide fuel cells (SOFC) for advance military power generation systems."

current density as determined by local gas compositions, and adjustable design assumptions including geometrical details, temperature, pressure, cell resistances, and other factors.

Based on the engineering calculations, complete SOFC module designs were prepared. The designs were based upon adaptations of current TMI small systems for operation on multiple fuels. Figure 3 shows the actual multi-module system demonstration including the electrical interconnection subsystem. Nominal power outputs of the module were up to about 1-kW. The modules were designed for parallel operation and automatic load sharing/load following.

Figure 3: Multi-module system powering Christmas tree and light bulbs

The overall system consisted of three subsystems: fuel cell power generation module(s), storage battery, and power conditioning. Alternative fuel circuits were used for different fuel types. For instance, gaseous fuels (natural gas and propane) used mass flow control valves during operation while liquid fuels (kerosene and biodiesel) used pumps. To minimize technical risks, the design approach drew heavily from previous TMI work, whenever possible.

Fuel Cell Subsystems

Subsystems included the following:

1. Fuel cell stack
2. Insulated stack mounting assembly
3. Heat exchangers, vaporizer, and reformer
4. Air blower or compressor

5. Water subsystem with pump
6. Fuel subsystems for natural gas or propane and kerosene or biodiesel
7. Cold-start subsystem
8. Sensors and controls
9. Power conditioning (on-board DC)
10. Interconnections, mountings, filters, enclosures, other

Storage Battery and Power Conditioning Subsystems

Deep-cycle lead acid batteries were employed for energy storage, because they provide a proven combination of good efficiency, high power capability, and long life when used in well-engineered systems. Lead acid batteries are also generally lower cost than most alternatives. The nominal ("C/20 rate") battery is rated at about 100 Amp-hours at 24 Volts.

The power conditioning subsystem combines the functions of a smart battery charger, dc-dc converters, and a true sine wave inverter producing single-phase 120 Volts rms at 60 Hertz. Maximum inverter power output is about 1500 Watts and 2250 VA continuous. True sine waves are generally required for high-quality power that can operate all types of residential loads without problems. The power conditioning subsystem included several types of protection equipment, including overcurrent and overvoltage.

Cell and Stack Fabrication

Cells and stacks fabricated for the program employed standard TMI fabrication techniques. Figure 4 shows a schematic representation of processing steps.

Figure 4. Typical Processing Schematic for TMI SOFC Stacks

Testing

System tests using natural gas and propane were used to determine standard fuel cell and system characteristics such as power density, efficiency, and time-based performance. In addition, tests

probed the boundaries of both stability and power capability. In addition, tests examined interactions of systems and subsystems relative to multi-module operation and load sharing.

Results and Discussion

Stack fabrication and system design and assembly was the focus for the first nine months of the program. Initial system tests focused on characterizing and verifying start-up and initial operating procedures. Stack loading, identified as a critical factor during operational start-up, required multiple modifications to the physical system and procedures to allow proper operation. Figure 5 shows an overall summary of all system runs during the course of the program. These runs studied system operation and identified hardware and operational problems that required further development or modification prior to commercialization.

Since the system was assembled primarily from off-the-shelf components and subsystems, it was not surprising to find many of the operational issues stemmed from the inherent limitations of the subsystems themselves. The unique nature of the hand-built hot subassembly also contributed to numerous issues. Initial issues were also identified in the multi-module electrical interconnection system. The commercial DC-AC inverter included internal “under and over” voltage protection circuitry requiring additional custom circuits to maintain the fuel cell system output voltage within the specified range.

The compression loading method used to immobilize the stack was found to be a critical factor in overall system operation. Loading issues were the cause of multiple stack failures. Examples included: fuel maldistribution within a stack, fuel maldistribution between multiple stacks, stack overheating, stack tipping, manifold seal failure, electrolyte damage, and stack electrical

shorting. The stack loading was modified several times to provide uniformity, both on a single stack and among multiple stacks.

Thermal management issues were found to have a significant impact on both single and multiple systems operations. Specifically, air and fuel system parameters and load impact thermal stability. The air system simultaneously provides overall system cooling and controls the stack temperature. The system was found to have two competing modes of operation that lowered temperature. Under certain conditions these cooling modes led to control instability, causing the system to fail. The problem was eventually overcome by forcing the airflow system to respond to only one mode.

The air cooling system is also sensitive to sensor operation. Thus, location of the thermocouple relative to the stack greatly impacted the accuracy and sensitivity of the measurement. Depending on the location of the thermocouple relative to the stack the sensitivity of measurement response could be modified. An example of system operating response is illustrated in Figure 6. As the system goes from closed circuit to open circuit the temperature spikes causing the compressor to begin increasing airflow (as indicated by the compressor current). Once the circuit is closed the temperature decreases and the compressor compensates, thus decreasing current and airflow.

Figure 6: System operating response example

In a two-system configuration, it was found that subsystem issues from one system had the potential to impact both systems. The systems were interconnected electrically on a common DC bus, thereby forcing all units to maintain a constant output voltage. Thus a transient problem in one system could impact the other system, as illustrated in Figure 7. In this run, an air controller problem in system 43 caused an unstable compressor response that led to an oscillating parasitic load, and an oscillating system temperature. This oscillating load in turn caused the overall system voltage to oscillate. In order to maintain a consistent bus voltage between the two systems, the voltage of system 44 also oscillated. Ultimately the controller instability caused

system 43 to attempt to control at the sub-stoichiometric air flow range, causing the system to rapidly lose voltage, shutting down both systems. More independent or consistent system operation is required before requiring alternative voltage bus control mechanisms.

Figure 7: Effects of transient problem in one system

In general, most components or subsystems required modification or adjustment. Table 1 lists some of the components or subsystems issues that impacted system operation and the resulting failure modes.

Table 1: Component and subsystem issues affecting operation

Component/Subsystem	Issues	Failure mode
Electrical Systems	Connection integrity, stability	Loss of power or control
Fluid piping	Fitting integrity, stability	Flow loss due to leaks
Controls	Tuning, output limits, sensor positioning	Control instability, loss of temperature control
Water Pump	Filter fouling, electronics failure	Reformer failure
Fuel Controller	Sensor fouling	System over-temperature
Insulation	Type and geometry	High temperature gradient
Stack Load	Positioning, installation	Stack leaks, reactant maldistribution

Ultimately, most off-the-shelf components demonstrated potential for successful operation. In independent testing, both the air compressor and the water pump operated continuously for over 9500 hours without failure. All systems were successfully operated concurrently for a total of 2700 hours of continuous operation on natural gas. Throughout the testing, the reforming catalyst did not coke (coking is an indication of inefficient fuel reformation).

System stability was sufficient to allow operation of the systems on multiple fuels. Over the course of the program, the system was run on natural gas, propane, and ethanol. Preliminary runs were run using biodiesel and kerosene, but limited due to budget constraints and the completion date of the contract. Figure 8 shows the system operating in the TMI conference room on propane fuel.

Most system characterizations were performed using natural gas. Figure 9 shows the power and net efficiency curves for a nominal 200 W DC net output system. A maximum 24% net efficiency was achieved at 225 W DC net power. As expected, gross power was found to increase at higher flows. However, cooling air requirements also increased, impacting total net power and net overall efficiency.

Conclusions

Over the course of this two-year program, TMI was able to design and build three independent kilowatt-class stand-alone systems. Construction experience gained from each system was iterative. Approximately twenty 300W class tests were conducted for an accumulated 15,000 hours test time with over 90% of that time on reformed hydrocarbon fuels. The system studies demonstrated the feasibility of operating multiple TMI SOFC systems and of operating on multiple fuels and showed that even at relatively low power (<300W) using one-third height stacks, net efficiencies near 25%

DC LHV on natural gas fuel can be achieved using standard balance of plant components. On-the-fly switching of hydrocarbon fuels (with no break in output power) was demonstrated, as was stand-alone operation on bottled propane.

However, the study also accentuated limitations of standard off-the-shelf components indicating a need for specialized subsystems, optimized for fuel cell operation. In particular, thermal management and control systems to maintain minimum temperature gradients and airflow rates were identified. The challenge is the time-scale response of the different systems. Electronic systems typically respond within milliseconds, fluid systems within seconds, while thermal system response can take minutes and even hours before achieving equilibrium conditions. Control algorithms that are effective over multiple-orders of magnitude difference in time scale may be necessary. Additional study is required to further characterize the operating parameters of the systems, particularly when multiple systems are run in parallel. Alternative control methodologies or systems may be necessary to minimize detrimental system interactions.